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## An Experimental Investigation of the Vortex-Breakdown Phenomenon

by

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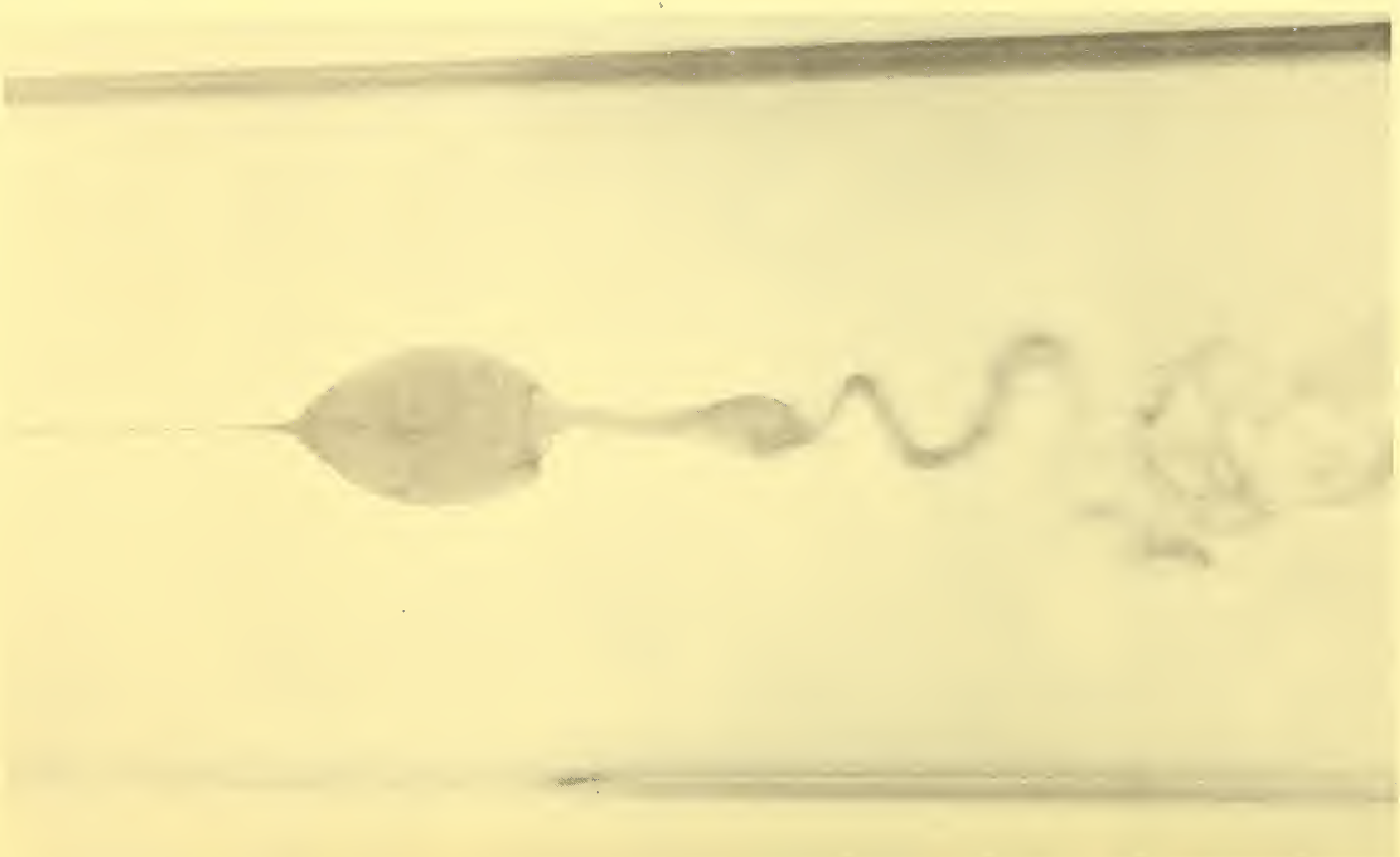

SUPERCRITICAL FLOW ⟶ BREAKDOWN + SUBCRITICAL FLOW (WAVELETS AND SPIRALLING CORE)

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ABSTRACT

The results of an experimental investigation of the characteristics of stationary and travelling vortex breakdowns in swirling flow in a diverging cylindrical tube are presented and discussed. Basically, three types of vortex breakdown were observed, viz., double helix, spiral and axisymmetric breakdown. The type and location of the stationary breakdowns were found to be dependent upon the Reynolds and circulation numbers of the flow. The breakdown bubble responded to gradual and abrupt changes in the upstream and downstream flow conditions in a manner analogous to the hydraulic jump in open-channel flow. The observations reported and the evidence presented herein revealed unmistakably that the vortex breakdown is a finite transition from a uniform state of swirling flow (supercritical) to one (subcritical) featuring a large standing wave, followed by standing wavelets, of finite amplitude.

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## INTRODUCTION AND REVIEW OF EXISTING INFORMATION

Since the discovery of the vortex breakdown phenomenon (an impressive structural change, generally liable to occur in any flow characterized by longitudinal vortices), Many theoretical and experimental studies have been conducted. The difficulties, both mathematical and experimental, involved in describing the nature, predicting the location, and identifying the occurrence of the phenomenon have been well documented (see, for example, Hall [1], p. 53 et seq.).

Vortex breakdown has been observed to occur over delta wings [2-11] at large incidences and in axisymmetric swirling flows in tubes [12]. In either case, different intermediate forms, between two extreme types of breakdown have been recognized. In the periodic spiral type of breakdown, the axial filament is deformed into a spiral configuration following an abrupt kink at a point slightly ahead of the apparent stagnation point. The sense of the spiral, according to the observations of Lambourne & Bryer [7] on delta wings, is <u>opposite</u> to the direction of rotation of the ambient flow (a result contrary to the observations reported herein for a confined flow). In the nearly steady and axisymmetric type of breakdown, a dyed filament of fluid along the axis of the core appears to spread symmetrically from the stagnation point and to enclose a quasi-stationary structure referred to as a "bubble." According to Harvey [12], "the flow downstream of the bubble showed no signs of a reversed core, but appeared rather to have returned to a form similar to that upstream of the breakdown." We shall discuss this observation in detail later and show that the bubble is neither closed nor does it contain a stagnant fluid.

Of the two forms of breakdown cited above, the spiral type is more commonly observed over a delta wing while the axisymmetric type generally appears in an axisymmetric swirling flow. Both forms appear to be far from "weak" non-dissipative transitions, particularly the axisymmetric type of breakdown.

The existence of these phenomena and other related anomalies to be described later, has considerable bearing upon the relative merits of various theoretical predictions regarding the nature and causes of vortex breakdown. According to Lowson [9] and Jones [13], the phenomenon, attendant to leading-edge vortices, always commences as a spiralling of the axial filament while the axisymmetric form is a later development of the primary spiral form. Lambourne [14] presented experimental evidence to the contrary and argued that the breakdown is initially axisymmetric but becomes unstable and finally changes into the spiral form. He suggested that the theory should first seek to explain the axisymmetric form and then discover the conditions under which it may degenerate into a spiral form. According to Ludwieg [15, 16] and Jones [13, 17] the stagnation of leading-edge vortices follows from a hydrodynamic instability of the vortex core with respect to spiral disturbances. Consequently, these investigators maintain that the breakdown ultimately exhibits the spiral form rather than the axisymmetric configuration.

Benjamin [18-20] (see also Refs. [21] and [22]) considered vortex breakdown as fundamentally a transition, akin to the hydraulic jump, from a uniforn state of swirling flow (supercritical) to one (subcritical) featuring axisymmetric standing waves of finite amplitude. His analysis was restricted to "weak" non-dissipative transitions between "adjacent" flows since it dealt exclusively with the flow of an effectively inviscid fluid which contained vorticity. Thus, the difference in the momentum flux of the two conjugate flows which he postulated had to be infinitesimal for circulation and total pressure to be preserved. As pointed out by Benjamin [19, p. 518], however, the results are not restricted to non-dissipative transitions since even the transitions involving substantial energy dissipation may still be regarded as a finite transition by virtue of the conservation of mass and momentum. Be that as it may, the most significant assertion of the analysis is that the transition takes place from a uniform state of swirling flow to one featuring stationary waves of finite amplitude. In other words, the transition is not just a Rayleigh type of jump between two sequent states of flow. In fact the waves are an essential consequence of the transition and an integral part of the analysis. The transition may appear like a Rayleigh type of jump between two uniform states of flow only when the wave-making action is so violent as to break the leading wave in the form of a burst of turbulence and completely obscure any other wave which might have followed the first one. Benjamin [20, p. 73] has further shown that "a solitary wave is the only steady disturbance that can arise in a supercritical swirling flow without change of energy or flow force," and that in order "to account for the formation of steady periodic waves upon a supercritical swirling flow, it is necessary to assume some slight loss of energy, just as was shown in the previous studies, to be necessary to account for undular hydraulic jumps and for internal bores."

The conjugate flow theory was recently subjected to scrutiny on theoretical grounds. Jones [23] concluded that "the concept of a transition in which waves appear, without energy loss, to provide a flow-force balance is invalid for swirling flows since this requires the creation of rotation without loss of energy." In fact, according to Jones, there is no reason to assume that waves will occur in swirling-flow transitions just because waves can, under certain circumstances, form downstream of a hydraulic jump. He proposed that a Rayleigh type of jump (supposed to come into existence as a result of an instability precipitated by vortex rings) be fitted into the concept of conjugate flow theory and the possibility of waves be ignored.

To date, there has not been a crucial test which emphatically supports or refutes Benjamin's elegant theory partly because of the difficulty of preserving the axial symmetry of the stationary transitions, and partly because of the difficulty of making quantitative measurements with travelling breakdowns. In fact, no axially symmetric standing waves have yet been observed in vortex cores under which the aforementioned mathematical conditions might be valid. So far, the applicability of Benjamin's theory to axisymmetric vortex breakdown has rested primarily upon the experiments of Harvey [12]. Granger's [24] experiments with surges, generated in a bathtub vortex, tended to substantiate the finite transition model for a "travelling-bore" type of vortex jump. Pritchard [25] generated solitary waves in a long cylindrical tube and demonstrated that such waves are possible in any swirling flow on which the angular velocity is distributed non-uniformly. Although the proof of the existence of periodic waves of finite amplitude and permanent form still remains as an important gap in the subject, the solitary wave is a necessary part of Benjamin's theory and the demonstration of its existence in swirling flows is an important step towards the acceptance of the finite transition model.

Hall [1, p. 101] noted that neither of the two theories discussed above (hydrodynamic stability and finite transition between sequent flows) need be associated with stagnation and that "a gross departure from the quasi-cylindrical state, can be identified equally well by any one of these proposals." He further noted that the results obtained from the quasi-cylindrical approximation are entirely consistent with the "stagnation" hypothesis advanced by Lambourne and Bryer [7], Gartshore [27], and Gore and Ranz [28]. The implication to be inferred from the identification of the occurrence of breakdown as a failure of the quasi-cylindrical-approximation is that the vortex breakdown is a necessary feature of swirling flows with sufficiently large swirl, and that no special mechanism is needed to explain its occurrence.

None of the theories cited above address themselves to the important question of the structure of the transition region. The understanding of the flow field resulting from the breakdown is of special importance for various reasons: the understanding of the amount of energy dissipation on the form and nature of transition, provision of specific information for the comparison of various predictions against each other and against experimental facts, and the prediction of pressures, forces, and moments acting on the adjacent body. Although the acquisition of the power of prediction of the occurrence of breakdown must necessarily be the first step in the analysis, additional progress towards the full understanding, control, and the possible use of vortex breakdown could only come from an experimental and/or theoretical mapping of the flow field in and around the transition forms.

Bossel [29] made an attempt to analyze the vortex-breakdown flowfield by reducing the equations of swirling motion to simpler sets in four different regions of the flow field and claimed to have obtained solutions which agree in all important aspects with experimental observations. Bossel further claimed to have introduced still another viewpoint into the existing reservoir of explanations of vortex breakdown. A careful examination of this work shows that Bossel's proposal is in essence identical with that earlier proposed by Hall [26], that the set of solutions are more or less structured towards the realization of a breakdown bubble (some of his boundary conditions are questionable), and that the predicted variation of axial velocity, flow pattern within the bubble and several other characteristics of the flow, do not agree with those observed experimentally.

Leibovich [30] examined the behavior of weakly non-linear waves in rotating fluids through the use of the Korteweg-de Vries equation and the several cases of critical stationary flows with reference to Benjamin's finite transition theory. He was able to predict, through the use of a uniform axial velocity and a Burgers-type tangential-velocity distribution, the shape of the vortex-breakdown eddy which appears to approximate the gross characteristics of the observed breakdown bubbles. Leibovich also attempted to establish similarities between unsteady features of the Korteweg-de Vries waves and the wavelets occurring downstream of the breakdown bubble. He suggested (with some reservation) that these wavelets or "solitons" are co-existing solitary waves with a tendency to slowly move away from the largest leading wave (the breakdown bubble). As will be noted later these wavelets or secondary waves do exist and remain stationary, in space and relative to the main wave, with no tendency to part company. Be that at it may, the approach taken by Leibovich has many interesting features and needs further exploration in the light of the observations to be subsequently described.

The foregoing review of the existing literature on vortex-breakdown phenomenon is by no means complete. There are a number of additional studies directly or indirectly related to transition in swirling flows. It is, however, already apparent that additional theoretical and experimental work is needed to reconcile all the differences in the observations and interpretations of this elusive but beautiful phenomenon. It is also apparent that the investigation of the characteristics of stationary breakdowns alone is not sufficient for the understanding of the basic mechanism leading to breakdown. The shortcomings of the various analyses and explanations (which appear to serve equally well to identify the occurrence of <u>stationary</u> breakdowns) may become apparent when tested under transient-breakdown conditions. The significance of the study of transient breakdowns has already been realized by Benjamin [20, p. 77] who stated that "...a wave train might be realized much more distinctly as a travelling disturbance, the counterpart of a progressive bore just as the usual vortex-breakdown phenomenon is the counterpart of a stationary hydraulic jump." In fact, Pritchard's [25] work was an outcome of this suggestion.

The present investigation was undertaken approximately three years ago for the purpose of designing and conducting critical experiments with which to examine the merits of the existing theories, to obtain detailed information on the flow field in and around the transition, to study the characteristics of the post-transition region, and finally to examine the response of the transition to transient super-and subcritical flow conditions.

## EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental equipment (see figures 1 and 2) consisted of a plexiglass water tank, adjustable swirl vanes, a diverging pipe, a constant head reservoir, a rotameter, and the necessary piping system.

The inside of the closed test tank was 130 cm long, 35 cm high, and 35 cm wide. The tank was maintained under 8 cm of water pressure by a simple overflow pipe placed in a small plexiglass box attached to the top of the tank. One of the end plates (downstream end) contained six inlets which were connected through a larger pipe to the constant head reservoir. Equal amounts of flow were passed through each inlet by properly constricting each supply line leading to the inlet. A honeycomb was placed outside the test pipe and wall-to-wall inside the tank near the inlet holes to further insure calm flow conditions. The maximum average velocity in the tank, outside the test pipe, was approximately 0.25 cm/sec.

The upstream end plate contained two small-bore orifices (0.008 cm) for the passage of dye. One hole was drilled at the center of the outer plate, and the other 5 cm above the first. Inside the tank, a second plate was attached to the upstream end plate. A streamlined, conic solid perspex piece, (center-body) the diameter of which was 16 cm at its base, was fixed to the inner plate. This piece served two purposes. First, it was part of the entrance channel which conveyed the fluid to the diverging test section. Secondly, it contained two small holes (coaxial with the small bore orifices in the outer end plate) for the injection of dye into the flow field. Swirl was imparted to the fluid by 32 streamlined foils (each 3.5 cm long and 2.74 cm wide) placed symmetrically in a circular array around the inlet piece. Each vane was fixed with one screw to the inner plate. A circular ring (1 cm wide, 0.4 cm thick, and 18.5 cm inside diameter) was fitted into the body of the inner plate.† The ring contained 32 small pivots, each one being approximately 0.3 cm long. These pivots were precision fitted to 1.5 cm slots carved in the edge of each vane. With this arrangement, the vane angle was set at any desired value between zero and 60 degrees.* The width of the passage between any two vanes changed with the particular vane setting but remained uniform along the passage since the included angle at the tip of each vane was 11.25 degrees (360/32, see figure 3). The average velocity of flow between the vanes for the maximum vane setting of $\phi$ = 60 degrees, was approximately 7 cm/sec.

As cited above, the streamlined entrance piece (center-body) attached to the center of the inner plate constituted part of the channel which conveyed the fluid to the diverging pipe. The outer wall of the channel was formed by another streamlined perspex piece. It was in turn coupled to the entrance of the diverging tube. This coupling was made in such a

†This ring could be rotated in its place by means of a simple lever-micrometer mechanism.

*Vane angle setting was adjustable to 1/120 of a degree.

manner that there were no protuberances at the junction. The test pipe and the bell-mouth assembly were externally adjustable vertically and laterally (with a wire and screw arrangement between the outer face of the test tube and the tank wall at a section sufficiently far from the vanes). The purpose of this adjustment was to align the dye line (and also the tip of the center-body) with the axis of the test tube. Failure to do so resulted in the development of an initially spiralling vortex core and attendant spiral disturbances.

The diverging tube, 25.4 cm in length with a 1.905 cm initial radius, constituted the test section. The angle of divergence of the tube was chosen to be 1.434 degrees ($\tan \alpha = 0.025$). The bell-mouth joined the diverging test tube through a 5.72 cm long and 1.905 cm radius uniform section which was machined as part of the bell-mouth. A round tube (5.08 cm I.D., and approximately 80 cm long) was smoothly coupled to the downstream end of the test section. The other end of the tube was connected, through a 4 cm long smooth reducer* embedded in the tank wall, to a 2.54 cm I.D. pipe outside the tank. The pipe conveyed the flow to a precision rotameter calibrated for a maximum flow rate of 18 litres per minute.

The dye injection tubes (one at the axis and the other 5 cm above the axis) were connected to two separate dye reservoirs (containing different

*The diameter of the exit hole in the reducer was varied from 1 cm to 2.50 cm in 0.5 cm intervals.

colors of dye for color photography) placed at suitable and easily adjustable elevations. Extreme precautions were taken to insure the injection of a straight and relatively slow dye filament. A small needle valve on the center dye-line allowed intermittent dye injection to be accomplished without imparting a flow force on the vortex filament.

Hypodermic tubing (suitably set at the end to an angle radially tangent to a mean surface between the center-body and the bell mouth) was inserted through the second dye-injection hole. It was moved longitudinally between the two streamlined surfaces in order to visualize streamlines at various radial distances from the axis of the test tube. The hypodermic tubing was first set longitudinally and then rotated slowly to its final position by comparing the slope of a suitable streamline (made visible by a drop of dye put on one of the vanes) with that of the dye issuing from the tip of the hypodermic tubing. This procedure insured the injection of the dye filament parallel to the direction of the local streamlines. The maximum Reynolds number of the flow about the hypodermic tubing was approximately 25.

An adjustable mirror covering the total length of the test section and part of the uniform conduit was installed inside the tank to enable the photographing of the top side of the vortex breakdown and the surrounding streamlines. During most of the tests, it was lifted up flush to the inner face of the top cover of the tank. Scale marks engraved at appropriate places on the test pipe and the mirror enabled the extraction of numerical data from the pictures projected on a large screen. Both still and motion pictures (black and white or colored) were taken with the fluorescent lights permanently placed under and behind the tank. Motion pictures were taken at various constant speeds ranging from 16 to 64 frames per second.*

Attempts to measure the circumferential and axial velocity distributions with a hypodermic tube (connected to a physiological pressure transducer) at a section immediately upstream of the start of the diverging tube were for the most part unsuccessful mainly because the pressure readings were relatively low (~0.5 cm of water). Additionally, the slowness of the response of the small-bore probe to the changes in pressure at various probe locations required an investment of time which was not compatible with the degree of accuracy of the measurements. Instead, one of the test tubes was fitted with wall pressure taps (normal to the bounding surface) located at 1.27 cm intervals along its length. Eight of the pressure taps were monitored simultaneously by connecting them to eight physiological pressure transducers which were in turn connected to a carrier amplifier and digital recorder system. The results yielded temporal mean values and were, as will be discussed later, quite satisfactory.

A hydrogen bubble technique was investigated for velocity distribution determination. It was immediately found that the wire could not be extended

*Shutter opening angle was 135 degrees. For each film speed, the exposure per frame is thus given by: 135/(360 x film speed).

across the entire diameter of the tube. When the wire was slowly and radially pushed into the test section while keeping the central dye-injection tube open, the flow pattern outside the core and the breakdown far downstream of the wire remained relatively unaffected until the tip of the wire barely protruded into the vortex core. At this point, a backflow pattern was set up right below the wire, producing an axisymmetric breakdown. When the wire was slowly withdrawn, the flow and the breakdown returned to their previous states. The apparatus was modified so that the wire would only come in from one side of the core and not extend across the entire diameter of the tube. Even then, the pulse timing problems and the buoyancy of the bubbles precluded sufficiently accurate representation of the flow field.

The position of the breakdown, relative to the point where the divergence of the tube started, was determined by setting the vane angle at a desired value and then changing the flow rate at suitable intervals, or by maintaining the flow rate constant and then systematically altering the vane settings.

# THE OBSERVATIONS OF THE VORTEX CORE

In the first series of experiments, the ratio of the tangential to axial velocity was varied by means of the adjustable vanes while maintaining the flow rate constant.

At a fixed flow rate (say at Re = 5000), the dye filament maintained a perfectly straight and laminar form throughout the length of the test tank for a zero degree vane angle setting. As the vane angle was slowly increased to 20 degrees, spiralling waves developed toward the end of the uniform tube and the filament became sheared into a tape which broke into turbulence after several revolutions in the form of a helix. As the vane angle was increased to 30 degrees, the filament decelerated rapidly near a point approximately six diameters from the start of the diverging tube, and the filament deformed, following an abrupt kink, into a spiral configuration. The spiral persisted a few turns and then broke into large-scale turbulence as seen in figure 4. The sense of rotation of the spiral was identical to that of the fluid surrounding the original filament. An additional small increase in swirl distorted the filament in such a manner that, after the first turn, it developed a tendency to curl back toward the kink as seen in figure 5. Subsequent increases in swirl resulted in two distinctly different forms of breakdown. The occurrence of either one of these forms depended to a large extent on the rate of increase of swirl and the setting of the center-body relative to the test tube, i.e., on the upstream disturbances. The first and more commonly observed form (figure 6) is the expansion and folding of the filament, before the completion of the first turn, all the way back to the kink. The subsequent motion of the filament and breakdown into turbulence are clearly visible in figure 6.

When the filament was perfectly centered, all air bubbles removed from the system, every precaution taken to eliminate internal and external disturbances, and the vane angle was increased extremely slowly (say 1/60 deg/sec) so as to arrive at the right combination of flow rate and swirl, the original filament gradually decelerated and expanded into a slightly curved triangular sheet as seen in figures 7 and 8. Each half of the continuous sheet wrapped around the other (<u>rotating in the same sense</u>) into the form of a double helix. This form gradually expanded and filled the entire test tube. Subsequently, it appeared to break into a very mild turbulence. This type of vortex breakdown, never observed in the previously reported studies, appeared to occur and sustain itself with very little energy loss. We shall, for this reason, call it mild or double-helix breakdown. Once it came into being, its appearance and location were quite steady and the intermittent injection of the dye did not disturb it, thereby allowing the determination of the axial component of velocity of the advancing dye filament from motion pictures. It is significant to note that the filament rapidly decelerated but did not stagnate.

Further increase of swirl produced an almost axisymmetric arrangement as seen in figure 9. The filament did not spread out suddenly and symmetrically in the form of a "tulip" but rather maintained its integrity for a short distance on one side of the reversed flow form and then expanded into an undular tape. The entire arrangement was quite unsteady and darted back and forth along the axis, in spite of the fact that both the swirl and flow rate remained constant.

For larger swirls or vane angles, the breakdown form moved progressively upstream and at a definite combination of swirl and flow, the bubble became a smooth and nearly symmetric body, as seen in figure 10. The original filament spiralled about the body (sometimes penetrating it, possibly due to inertia effects related to the slight density difference between the dye and water) and near the downstream end expanded into a triangular tape, part of which spiralled rapidly into the bubble with the remainder spiralling about a relatively larger filament shed from a portion of the vortex ring trapped in the bubble. After a distance of approximately one bubble length, the new core often deflected, following an abrupt kink, into a loose spiral configuration as seen in figure 10. This spiral never formed another bubble, possibly due to instabilities just described, and after a few turns broke into large-scale turbulence. Under rare circumstances, however, the new core formed another stationary but relatively smaller bubble or wavelet (figure 11) which persisted for a few seconds before it reverted to the aforementioned spiral configuration. It must be noted before proceeding further that no alterations were made either in the diverging tube or on the existing flow conditions to help the formation of the second wave. The rarity of the formation of the second bubble or wave is not too difficult to understand if we remember that the adverse pressure gradient resulting from both the strong divergence of the test tube and the formation of the first bubble causes a strong rather than a weak jump, the pressure instabilities in the wake of the first bubble are quite strong, and that the new vortex core, in a subcritical state, as well as the second wave are strongly influenced by the instabilities generated further downstream by the spiral breakdown and turbulence. Be that as it may, the existence of a second wave has now been experimentally demonstrated without the insertion of flow-accelerating schemes. Obviously, the existence of a standing second wave is of greater importance than the first one as far as the "conjugate flow" theory is concerned.

Following the observations and recording of the second wave in the diverging tube, steps were taken to alter its size and distance from the first breakdown. For this purpose and following the efforts of Harvey [12], a second plexiglass tube was fitted exactly inside the downstream half of the diverging tube. The outer radius of this insertion varied from 2.223 cm to 2.54 cm and the inner radius remained constant at 2.223 cm. The length of the insertion was 12.7 cm. Thd downstream end of the insertion (which had a wall thickness of 0.32 cm) was rounded over a 2 cm length to smoothly increase its inner radius to 2.54 cm, the radius of the uniform tube downstream of the diverging tube. When the system was turned on and the flow conditions properly set, the first breakdown bubble formed all by itself (no prompting was necessary) and exhibited new and remarkable features. These features which will be described below were both stable and repeatable. Figure 12 shows clearly two breakdown waves, the first in the diverging tube and the second in the insertion. The flow, following the second wave, broke into large-scale turbulence without first forming a spiral type of breakdown. When the first wave was moved further upstream, by slightly adjusting the Reynolds number of the flow (this will be explained later), the effect of the insertion on the shape of the first breakdown as well as on the subcritical swirling flow following it became quite apparent. As seen in figure 13, the bubble became almost spherical, the intensity of the instabilities at its downstream end considerably reduced, and the length of the new vortex core increased. The conclusions to be drawn from the foregoing observations are self-evident: Wavy flows can and do arise from vortex breakdown and the type and distance of the subsequent waves depend on the conditions imposed on the evolution of the subcritical flow downstream of the breakdown bubble.

Following the completion of the experiments just described, the insertion was removed and a series of further experiments was performed in order to understand the motion of fluid within and outside the bubble. Another filament was introduced away from the axis of the center-body and its evolution around the bubble was observed. The upper photo in figure 14 shows that the outer filament remains laminar and relatively unaffected at the section where the central filament finally breaks into turbulence. The lower photo, which was obtained by stopping the injection of the center dye filament, shows that the outer stream surfaces expand around the bubble and that the flow pattern downstream of the bubble remains visible in spite of the absence of upstream dye injection. In fact, the bubble and the tail configuration remained visible for as long as 20 seconds. The tail configuration could not have remained visible during all that time period had the bubble been closed and had the spiralling core downstream of the bubble not been issuing from the bubble (the discharge mechanism will be described later). In fact, the tail configuration becomes invisible only when the bubble is in a state of growth.

Following the establishment of the gross characteristics of the symmetric breakdown, different kinds of additives were introduced into the central dye reservoir for the purpose of more closely examining the behavior of the vortex core in front of and surrounding the bubble. One series of experiments was conducted with the addition of fluorescent "marker dye." The specific gravity of the mixture was very close to unity. Observations have shown that the filament spiralled on the front face of the bubble with an ever-increasing radius and then either penetrated the bubble or continued as part of the flow downstream of the bubble. Those parts of the dye which penetrated the bubble found their way to the axis of the bubble and took the form of a screw-worm. They moved at first slowly (from a point near the upstream stagnation point to the mid-length of the bubble) and then extremely rapidly and were literally ejected from the bubble. Those portions of the dye which found their way to the downstream end of the bubble expanded, as explained before, into a tape, part of which spiralled upstream into the bubble and part downstream, around the new and relatively thicker vortex core, which continuously issued from the bubble. A toroidal vortex, captured at the downstream half of the bubble, was clearly visible at all times. The axis of the vortex ring gyrated at a regular frequency about the axis of the tube. The fluid in the bubble was replenished from the side of the bubble nearer the downstream portion of the ring and emptied from the side farther from the upstream portion of the ring (see lower photo in figure 14). This simultaneous filling and emptying process, possibly due to pressure instabilities in the wake of the bubble, resulted in a new vortex core downstream of the bubble which behaved like a gyroscope processing about the axis of the tube with a rate of precession equal to the rate of gyration of the axis of the vortex ring.

Another series of experiments was conducted by adding glycerine (10% by weight) into the dye solution (water, methylene blue). The viscosity of the mixture was 1.3 times that of water. The observations may best be described with figures 15-17. The filament decelerated rapidly, formed an abrupt kink approximately 0.1 bubble diameter in front of the bubble and then smoothly followed the outer surface of the bubble. At the downstream end of the bubble, the filament once again divided smoothly and followed the motion previously described. For very low methylene-blue concentrations, the bubble was practically invisible, while the filament with the kink was clearly visible and looked like a spoon holding the bubble.

## THE OBSERVATIONS OF THE TRAVELLING VORTEX BREAKDOWNS

A series of experiments was conducted to determine the response of the breakdown to relatively small changes imposed on the upstream swirling flow. These changes were produced in various ways: by increasing the inlet flow rate; by releasing a small air bubble from one of the side vanes; by oscillating one of the vanes; by oscillating the hypodermic tubing used for the eccentric dye injection; and finally, by varying the setting of all vanes.

With a very rapid increase of swirl (increasing vane angle), the bubble first moved (after a measurable time lapse) a short distance (approximately $0.2D_o$) downstream and then rapidly upstream, overshooting its final steady-state position by a distance of about $0.2D_o$. Then the bubble slowly moved backwards ($\sim 0.2D_o$) to its new final position. A rapid decrease of swirl resulted in similar motions in reverse directions.

The diameter of the bubble, which was approximately $0.3D_o$ for the steady state, increased rapidly during the downstream motion of the bubble and decreased when the bubble moved upstream. In fact, when the swirl was increased and finally the bubble began to rapidly move upstream, its diameter reduced to about $0.2D_o$ and the length of the bubble increased by approximately 30 percent. When the bubble reached its final steady-state form, its length-to-diameter ratio was found to vary between 1.45 and 1.55. The bubble reached its maximum diameter at a distance approximately 60 percent of its length from its front stagnation point.

These experiments clearly demonstrated that the changes imposed on the flow from upstream affect the vortex jump only after a new upstream swirling-flow condition is established and only after the axial velocity of the fluid within the vortex core is modified in accordance with the new swirling flow conditions.

Another series of experiments was conducted to determine the response of the breakdown bubble to relatively small changes imposed on the <u>downstream flow conditions</u>. When the flow was <u>decelerated</u> by constricting the exit hole at the downstream end of the test tube, the breakdown rapidly <u>moved upstream</u> (after a measurable time lapse) and often reached the center-body in the form of a reversed turbulent core. Figure 18 shows the motion of the bubble relative to the surrounding stream. It is most important to note, by comparing the successive frames in figure 18, that while the bubble propogated considerable distance upstream along the axis of and relative to the surrounding helical coil, <u>the swirling flow upstream of the bubble remained practically unchanged</u>.* A new upstream swirling flow condition was set up shortly after the bubble had reached its farthest upstream position. Then, depending on the last position of the bubble, either the same bubble or a new one which emerged near the center-body moved downstream and came to rest at a point where it would have occurred had the flow been originally set at a rate equal to that of the decelerated flow.

*Motion pictures show this remarkable phenomenon in a most convincing manner.

When the downstream flow was accelerated by rapidly enlarging the exit hole at the end of the test tube, the bubble rapidly moved downstream. Then, after a short time (sufficient for transmission of the "acceleration information" to the flow at the vanes), either the existing breakdown (if it were not already washed out) began to move upstream (see figure 19), and/or a new bubble abruptly came into being upstream of the original position and finally settled at a point where it would have occurred for the new flow rate, had the latter been constant. Under rare circumstances, however, when the rate and duration of the acceleration of the downstream flow were set just right, the original wave rapidly moved upstream and joined the new wave which just came into being (see figure 20). It should be noted in passing that a breakdown which abruptly came into being, under the conditions cited above, was, at least initially, always axisymmetric. Furthermore, during the period of growth, the bubble was filled with fluid by a perfectly axisymmetric re-entrant jet and there was no partial discharge of flow through a swirling jet as previously described in connection with stationary breakdowns.

The swelling of the vortex-core filament, disappearance of the dye filament (because of re-entrant jet feeding) immediately downstream of the nascent bubble, and the evolution of a gyrating tail are clearly visible in figure 21. Throughout this process, the outer filament upstream of the bubble remained unaltered whereas the helical filament downstream of the bubble rapidly accommodated the new flow conditions.

# MEASUREMENTS

Qualitative observations of the bubble were followed by quantitative measurements of the breakdown location, swirl angle, the axial velocity of the dye front, and the wall pressure distribution in terms of the flow rate and swirl.

The mean breakdown location was determined by first maintaining the flow rate constant and setting the vane angle at desired values or by maintaining the vane setting and changing the flow rate. In either case, the results did not differ significantly, and the data shown in figure 22 were obtained. Evidently, the type and location of the stationery breakdown are functions of Reynolds and circulation numbers* in the range of Reynolds numbers investigated; for smaller swirls, the axisymmetric breakdown occurs at higher Reynolds numbers; and finally, there is a region along every constant circulation line where there are two stable breakdown conditions, i.e., there is a region of "vortex breakdown hysteresis." As the flow rate was slowly increased while maintaining the vane setting fixed, the spiral breakdown moved upstream but maintained its form. Conversely, when the flow rate was slowly decreased in this region, the symmetric breakdown moved downstream.

*$Re = U_o D_o/\nu$ and $\Omega = \Gamma/U_o D_o$ where $U_0$ is the mean axial velocity at the entrance to the diverging tube and $D_o$ (3.81 cm) is the upstream diameter of the diverging tube. For $\Gamma$ see figure 3.

In the region of hysteresis, both forms (spiral and axisymmetric) were highly unstable and transformed into each other depending on the small disturbances introduced from upstream (abrupt slight increase of vane angle or center-body motion). A similar hysteresis effect was observed by Lowson [9] over delta wings with increasing or decreasing incidence in the range of 35° to 45° angle of incidence.

The swirl distribution, a short distance ahead of the breakdown, was determined by injecting dye from the second dye-injection line at various distances away from the surface of the center body. The helical streamline and its mirror image were photographed in a manner similar to that described by Harvey [12] and the data shown in figure 23 were obtained. The swirl angle distribution was found to be a function of the breakdown form. For the axisymmetric form, the maximum angle was about 50° and independent of the Reynolds and circulation numbers. For spiral breakdown, the maximum swirl angle varied from about 38° to 45°, depending on the intensity of circulation, i.e., in the regions where spiral breakdown occurred, the total circulation was appreciably less than that where axisymmetric breakdown existed.

The axial velocity of the dye front along the vortex core was determined from the motion pictures by interrupting the dye injection. It was assured that the interruption of the dye did not affect the position of the breakdown and that the breakdown was of the perfectly smooth and stable type. The pictures in which the bubble moved (within a time interval of 0.3 seconds) were not used in the velocity determination. The representative results are shown in figure 24. The general trend of the variation of the axial velocity is similar to that predicted by Hall [26] who has shown that the axial velocity undergoes, for sufficiently large swirls, a pronounced deceleration as a prelude to stagnation both when the bounding stream surface is cylindrical and when it expands. It is not possible at this stage to make an accurate comparison between the experimental results presented herein and Hall's predictions since the initial and boundary conditions assumed by Hall are, as has been pointed out by him, to a certain extent arbitrary and the numerical method employed is strictly applicable to laminar flows only. It is, however, clear from the data presented herein that the linear variation of the axial velocity predicted by Bossel [29] is not compatible with the observed facts.

Representative wall pressure distributions are shown in figure 25. As previously observed by Kirkpatrick [31], there is a slight positive pressure gradient upstream of the breakdown and a negative gradient immediately downstream.

Figure 26 is a plot of the contour of a representative axisymmetric breakdown bubble. Both axes of the plot were normalized with the local radius of the tube measured at the front stagnation point of the bubble. Even though this shape was fairly common and the over all dimensions of the stationary bubble did not significantly change with either the circulation or the Reynolds number of the flow, the sensitivity of the bubble shape to changes in the downstream conditions (a reduction in tube diameter) and to the motion (forward or backward) of the bubble must be remembered and the contour presented in figure 26 must be compared with those predicted theoretically with some caution and with the full remembrance of the divergence of the test tube.

## RESUME OF FINDINGS

(i) There are three basic types of stationary vortex breakdown, viz., double helix, spiral, and axisymmetric. The type and the shape of the intermediate forms depend upon the particular combination of the Reynolds and circulation numbers.

(ii) The response of each breakdown-form to changes imposed on the upstream or downstream flow conditions is analogous to that of a hydraulic jump between two sequent states of flow. The constricting effect of the tube wall and the swirling nature of flow prevent a precise identification of the corresponding physical features of the two flows.

(iii) The characteristics of the birth, growth, and motion of the breakdown wave, and many other observations reported herein unmistakably prove that the vortex breakdown is an abrupt change in flow structure and is not preceded by the amplification of travelling-wave disturbances in the usual manner of hydrodynamic instabilities.

(iv) Experiments with transient downstream conditions clearly show that the initial disturbance is comprised of a nearly symmetrical swelling of the vortex core, enclosing a region of circulating fluid. Instabilities in the wake of the bubble often render the motion unsteady and only the rudiments of a wave train can be observed. Under rare or specially controlled circumstances, however, the existence of a wave arising from vortex breakdown can be witnessed.

(v) No simple explanation can be offered regarding the difference in the sense of rotation of the spiral breakdown relative to that of the ambient flow in a tube and a leading-edge vortex.

(vi) The static pressure variation along the wall of the tube yields no new information other than that already revealed by the measurements of Kirkpatrick [31]. It may become important in checking the results of theoretical calculations.

(vii) The significance of the double-helix breakdown and its relation to the existing theories is not yet clear and requires further investigation. Its occurrence, with very little or no energy loss, and without the formation of a bubble, is certainly significant, and might require the re-examination of the analysis of very weak undular transitions.

## CONCLUSIONS

The observations reported and the evidence presented herein reveal unmistakably that the vortex breakdown is, as first propounded by Benjamin [18], a finite transition between two sequent states of a swirling flow and not a consequence of ordinary hydrodynamic instabilities. The stationery breakdown may be of spiralling or axisymmetric type and may change from one form to the other depending on the flow conditions. However, when the flow is perturbed such that additional waves are liable to be precipitated in it, then the initial disturbance takes an axisymmetric and not a spiral form. It does not, therefore, appear that the spiral disturbances have any bearing on the theory of infinitesimal transitions for swirling cylindrical flows. The same may not of course be true for non-cylindrical, unconfined, swirling flows.

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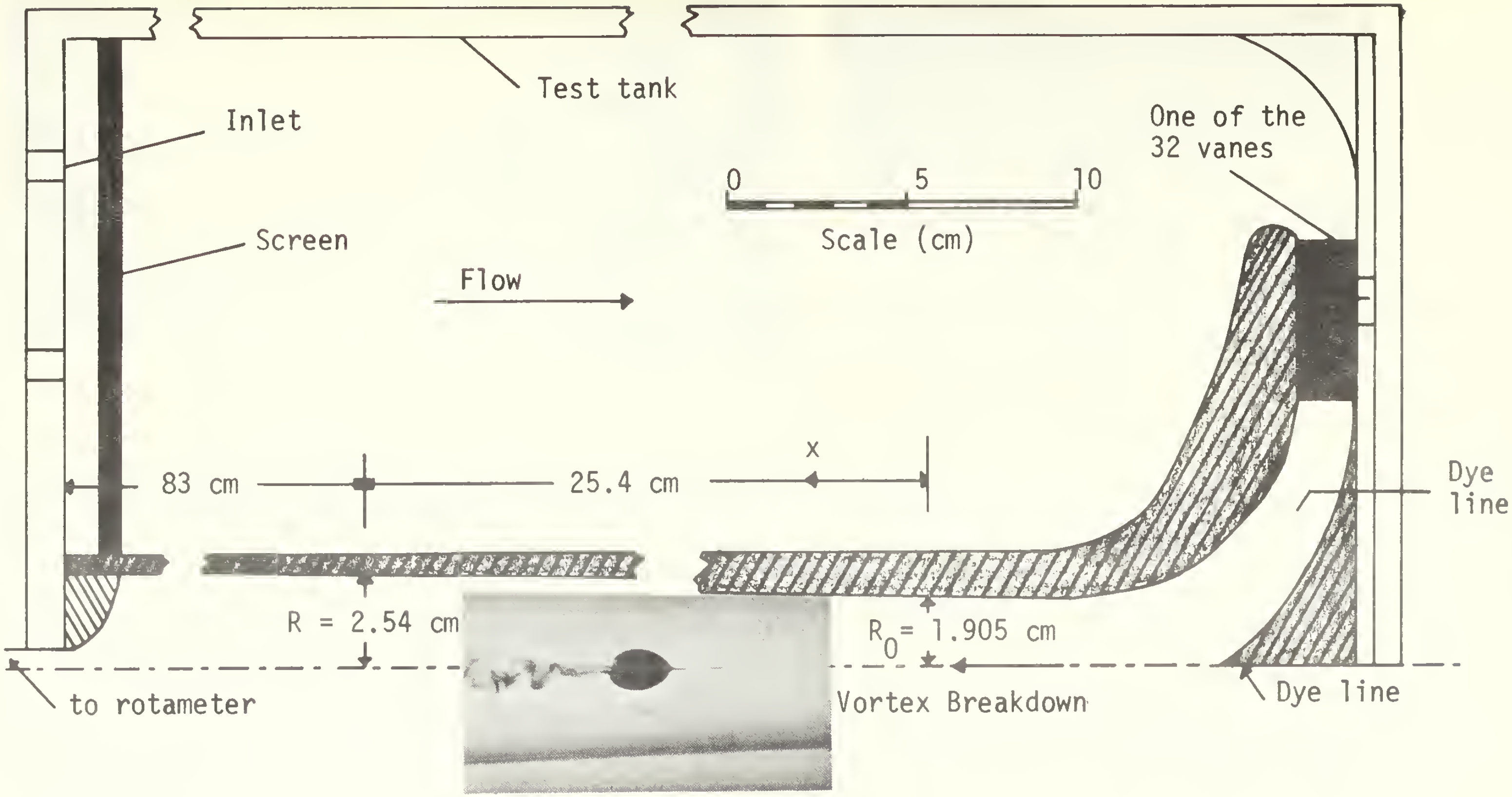
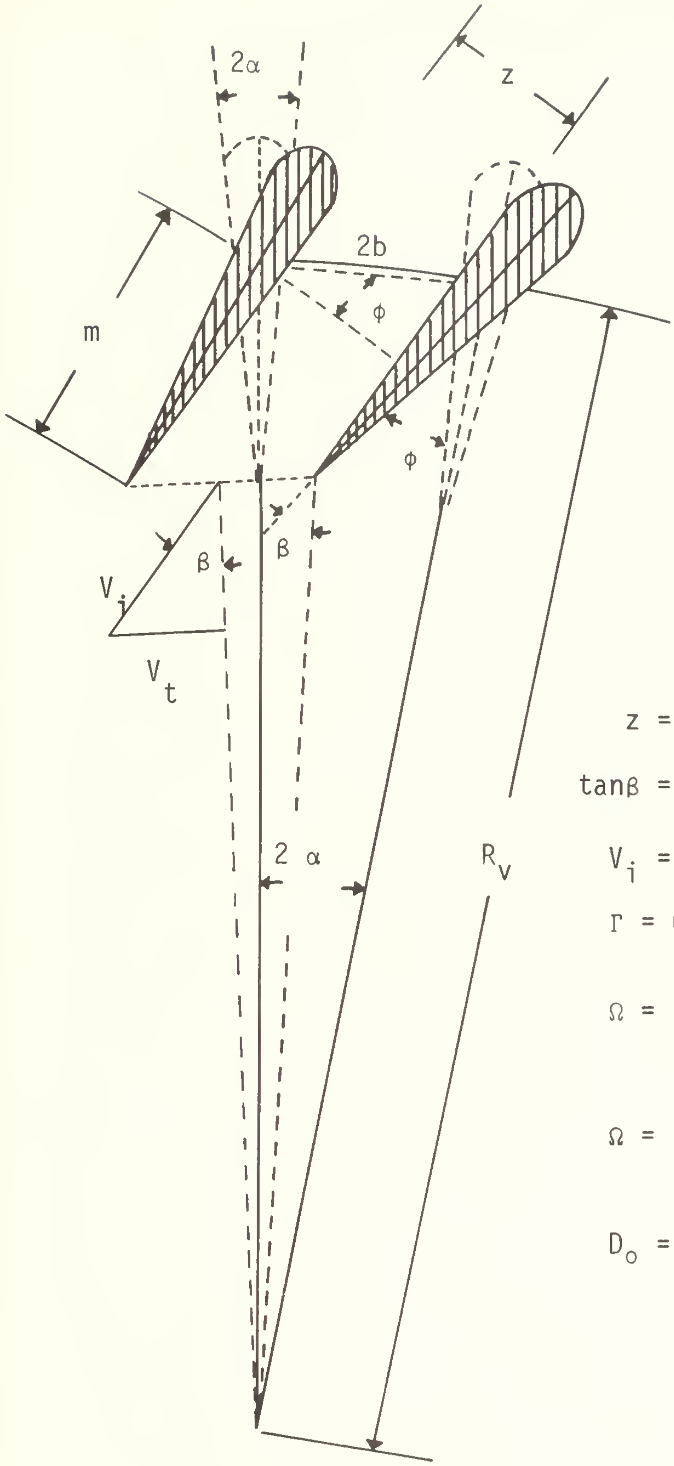



FIG. 1 TOP HALF OF THE EXPERIMENTAL APPARATUS

FIG. 2 VARIOUS VIEWS OF THE EXPERIMENTAL APPARATUS




$R_v = 10.65$ cm

$m = 3.5$ cm

$w = 2.74$ cm
(width of vane)

$\alpha = 5.625$ deg.

$b = \pi R_v/32$

$$z = 2b \cos\phi - 2m\alpha$$

$$\tan\beta = \sin\phi \,/(\cos\phi - m/R_v)$$

$$V_i = Q/32wz \ , \quad Q \text{ (total flow)}$$

$$\Gamma = 64\pi(R_v - m\cos\phi)V_i \sin\beta$$

$$\Omega = \Gamma/U_o D_o$$

$$\Omega = \frac{\pi^2 D_o(R_v - m\cos\phi)}{2\,w\,z}\sin\beta$$

$$D_o = 2R_o = 3.81 \text{ cm}$$

FIG. 3 VANE GEOMETRY AND THE CALCULATION OF THE CIRCULATION NUMBER $\Omega$

FIG. 4 INITIATION OF THE SPIRAL VORTEX BREAKDOWN

FIG. 5  EFFECT OF INCREASING SWIRL ON SPIRAL BREAKDOWN

FIG. 6 THE NASCENT STATE OF THE AXISYMMETRIC VORTEX BREAKDOWN

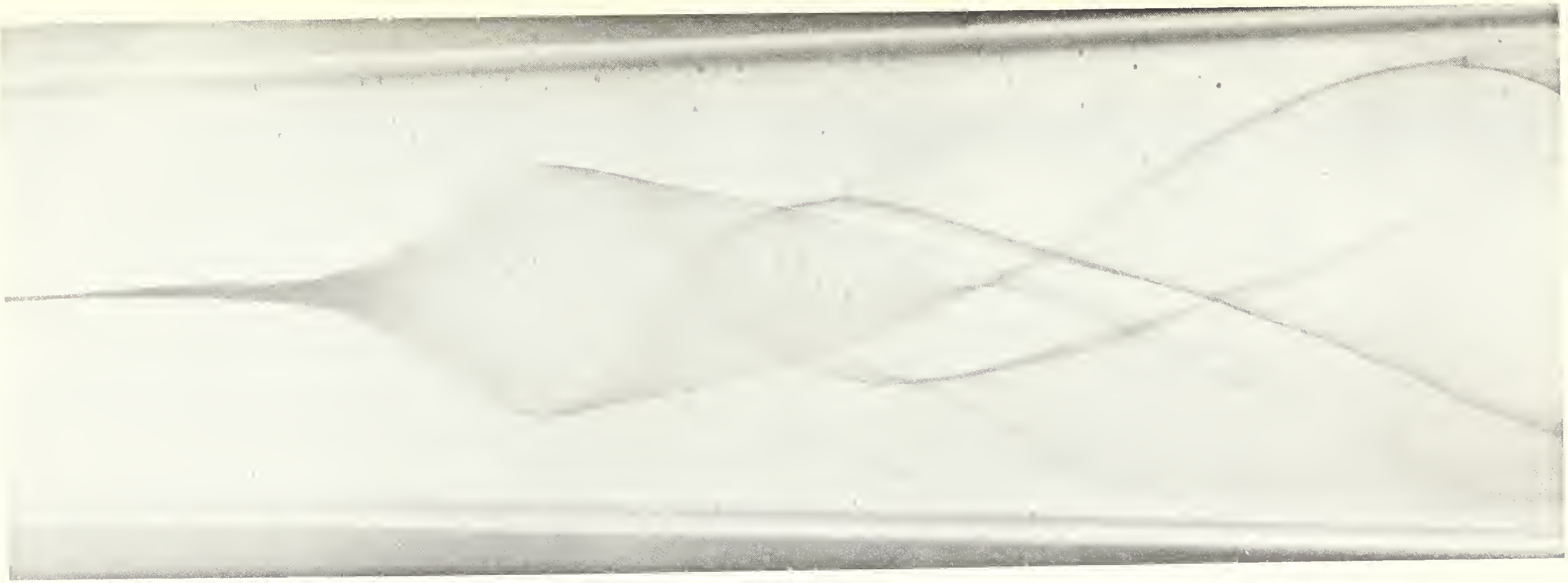


FIG. 7 DOUBLE-HELIX VORTEX BREAKDOWN (Re = 1150 , Ω = 94)

FIG. 8 DOUBLE-HELIX VORTEX BREAKDOWN (Re = 1700 , $\Omega$ = 75)

FIG. 9  INCEPTION OF THE NEARLY SYMMETRIC BREAKDOWN

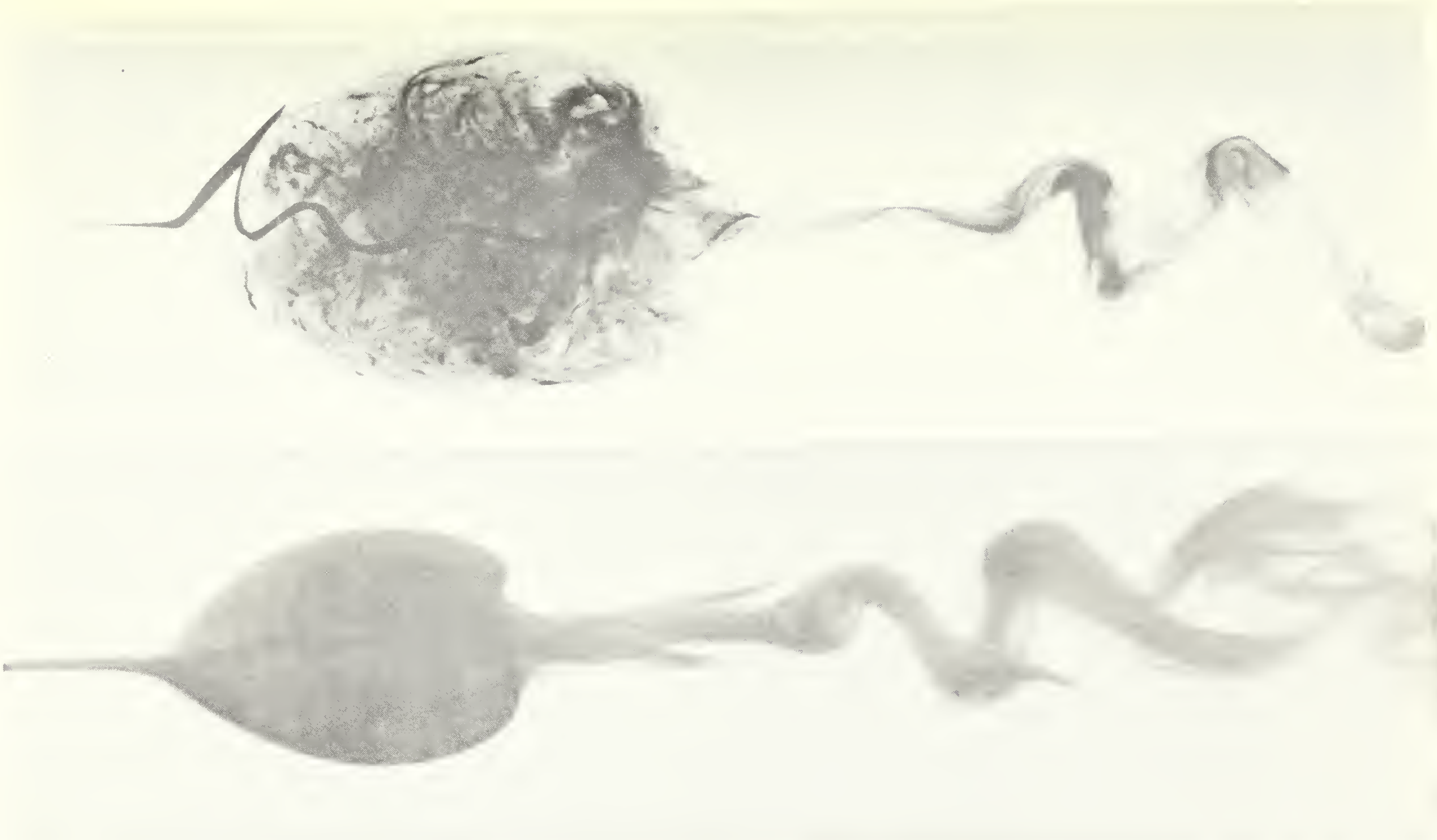


FIG. 10 AXISYMMETRIC VORTEX BREAKDOWNS

FIG. 11 FORMATION OF THE SECOND BUBBLE OR WAVELET

................ INSERTION .......................

FIG. 12 FORMATION OF A SECOND WAVE INSIDE THE INSERTION

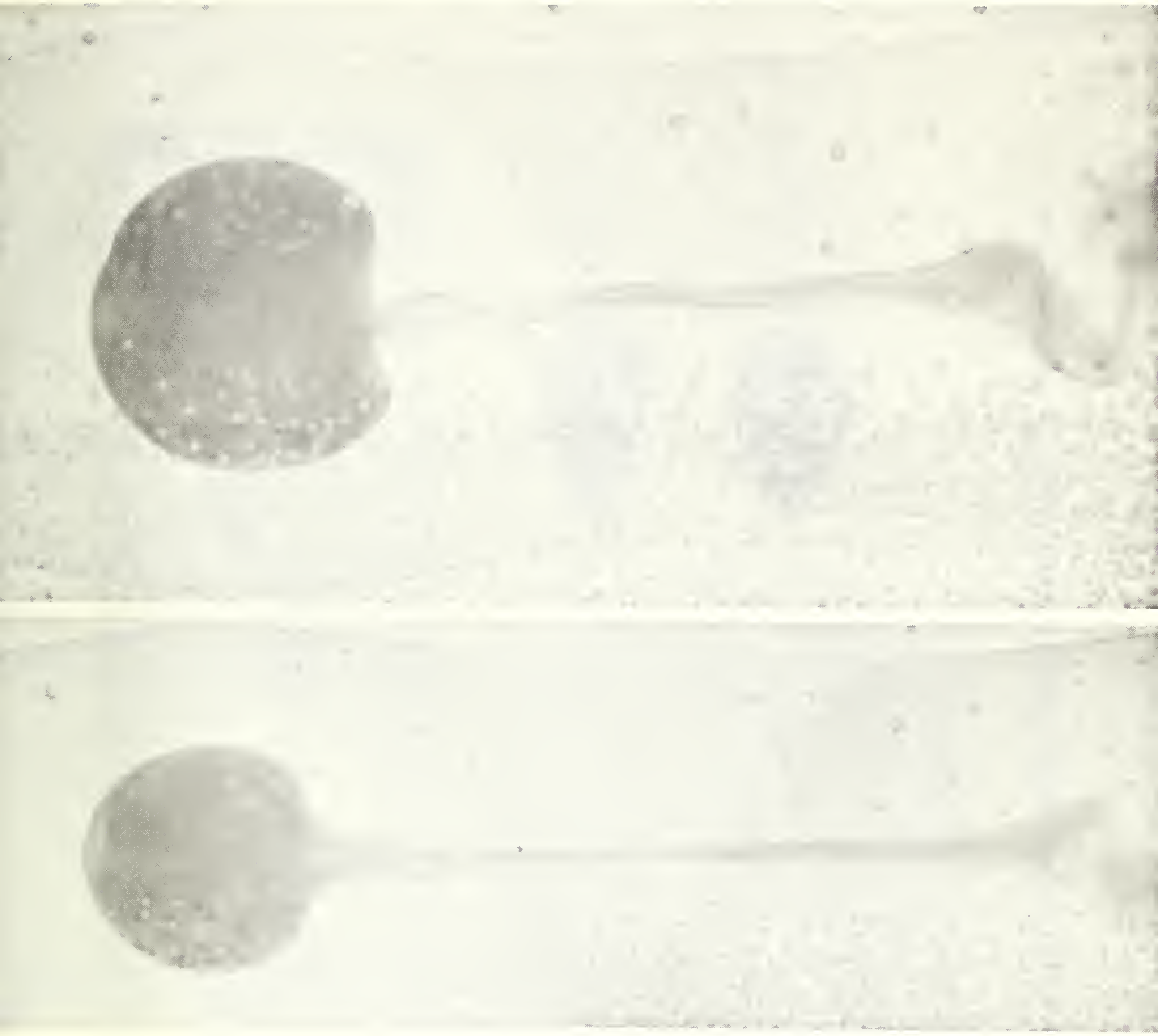


FIG. 13 THE EFFECT OF THE INSERTION ON THE BUBBLE SHAPE
(The insertion is further to the right of the spiral breakdown).

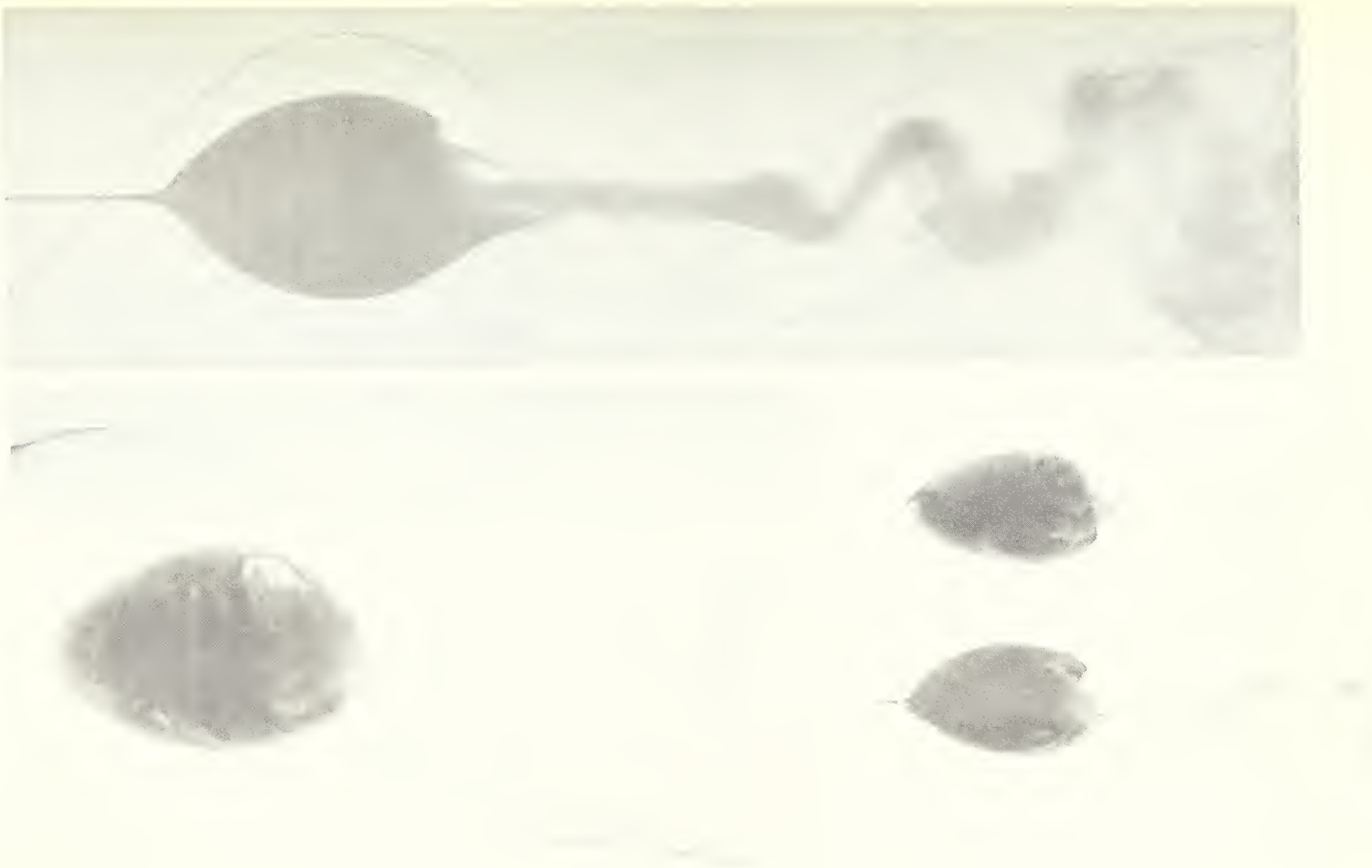


FIG. 14 STABILITY OF THE OUTER FILAMENT, TOROIDAL VORTEX, AND THE EMPTYING PROCESS

FIG. 15 THE PATH OF THE VORTEX CORE WITH 10% GLYCERINE ADDED TO THE DYE
(The formation of another toroidal vortex in the second bubble downstream of the first breakdown is clearly visible)

FIG. 16 THE DIVISION OF THE VORTEX CORE AT THE DOWNSTREAM END OF THE BUBBLE AND THE DEMONSTRATION OF THE EMPTYING PROCESS

FIG. 17 THE PATH OF THE VORTEX CORE
(The picture was taken shortly after the dye was turned on)

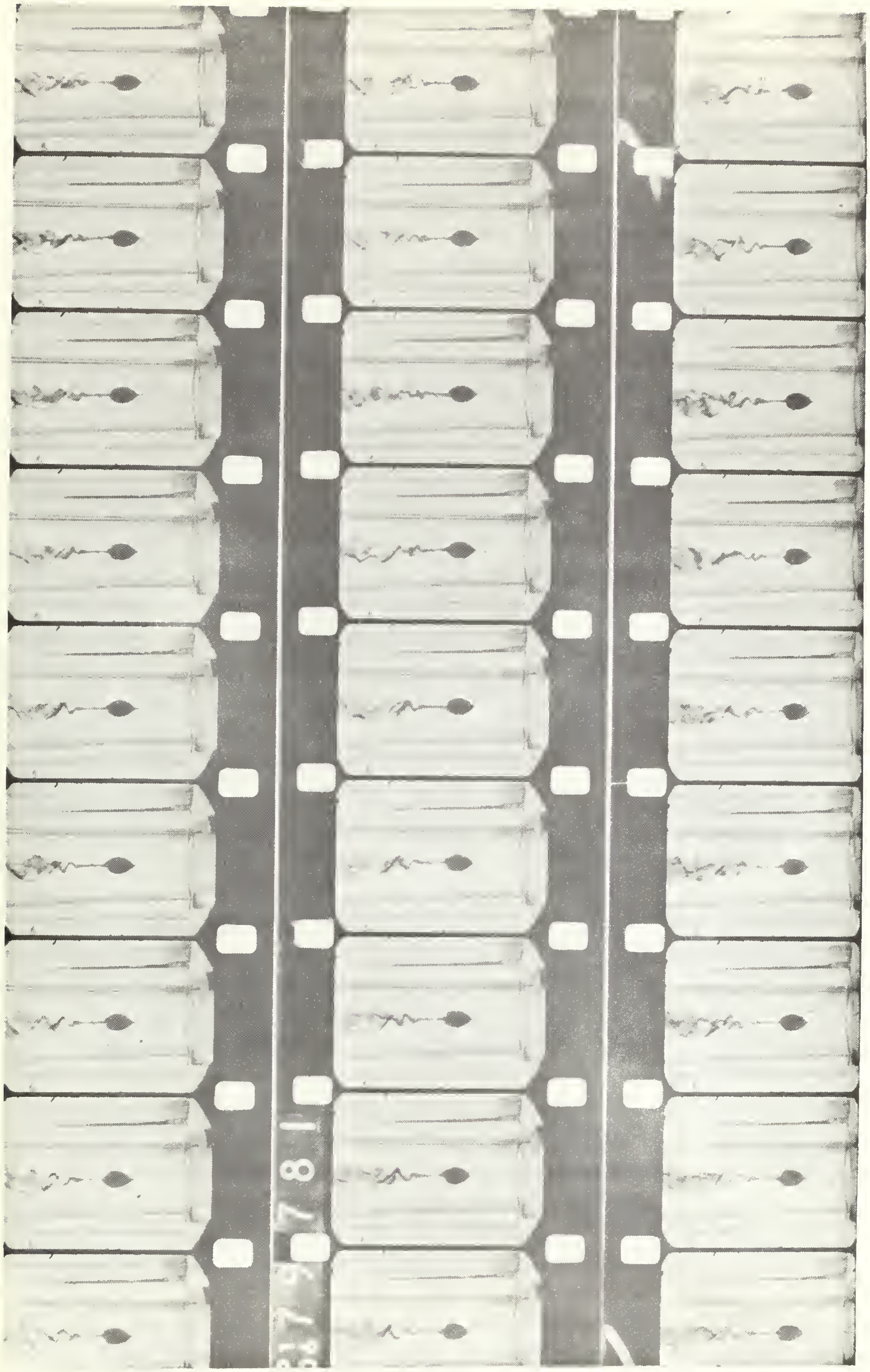


FIG. 18 The motion of the bubble relative to the surrounding stream. The motion picture was taken shortly after the flow was decelerated by constricting the exit hole at the downstream end of the test tube. Frames follow from top to bottom starting at the upper left hand corner. It should be noted that the flow ahead of the bubble remains unaffected. The change of the swirl angle, evolution of the wake, and the gyration of the new core are clearly visible. The film speed was 16 fps.

FIG. 19 The birth and growth of a bubble and the propagation upstream of a travelling breakdown. The axial symmetry of the initial disturbance, the evolution of the steamlines between the two disturbances, and the inability of the waves to propagate into the supercritical flow are clearly visible.

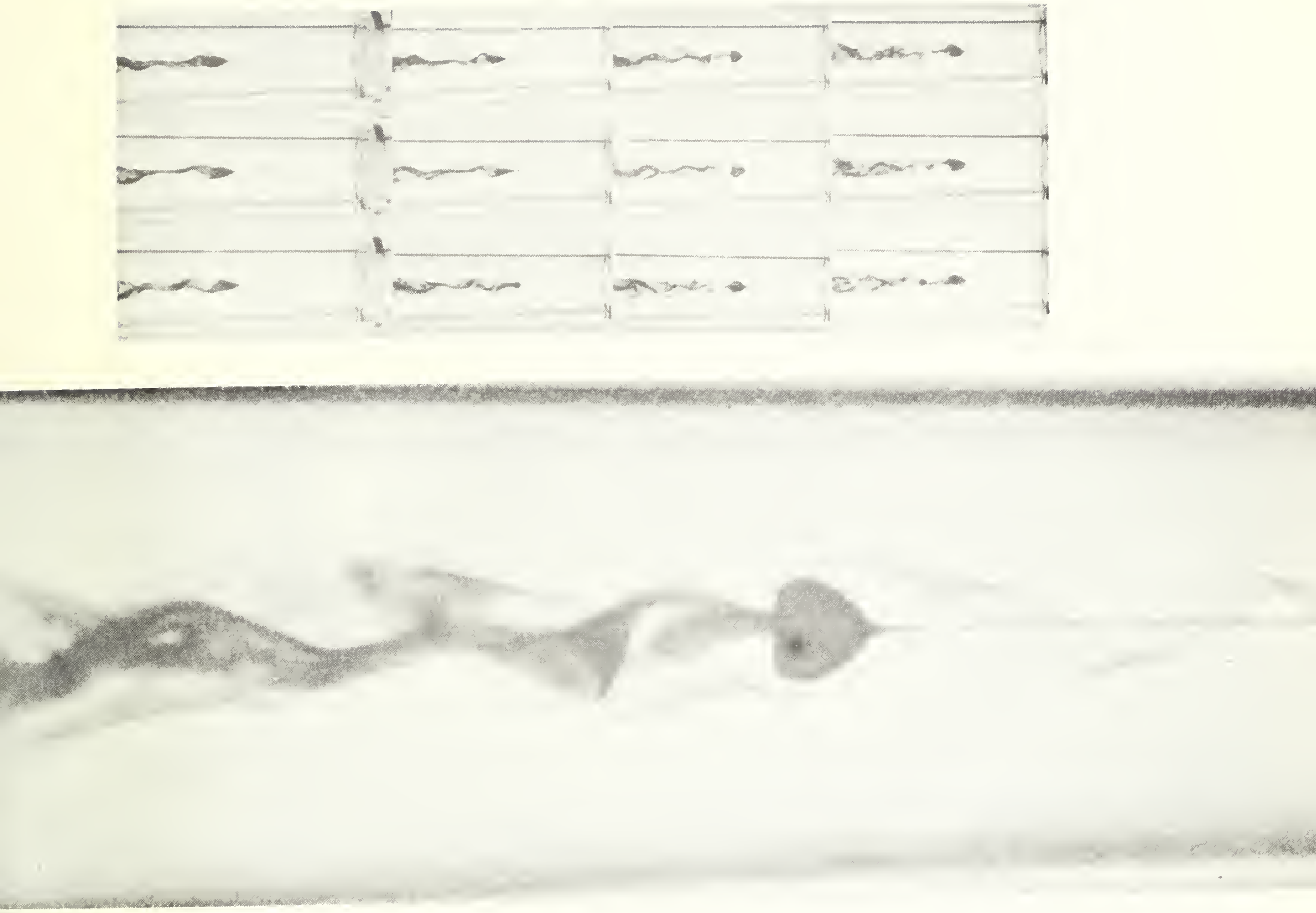


FIG. 20 The birth of a bubble and the propagation upstream of an existing breakdown: This pictures shows that the flow between the new and the old wave rapidly transforms into a subcritical state, the new breakdown is axisymmetric at birth, and that there are no waves or disturbances in the supercritical flow upstream of the new bubble. The lower photo shows the rudiments of a wave train.

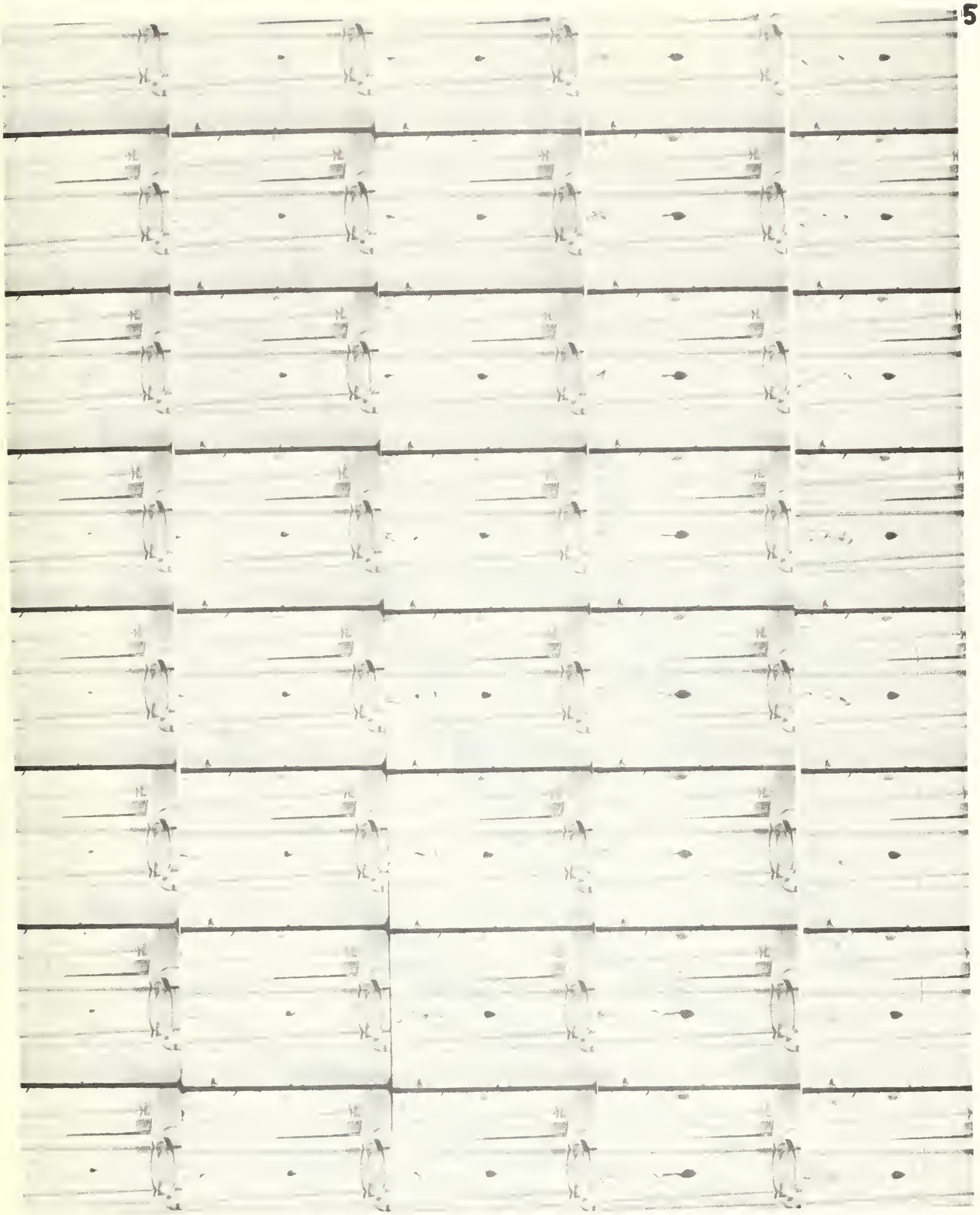
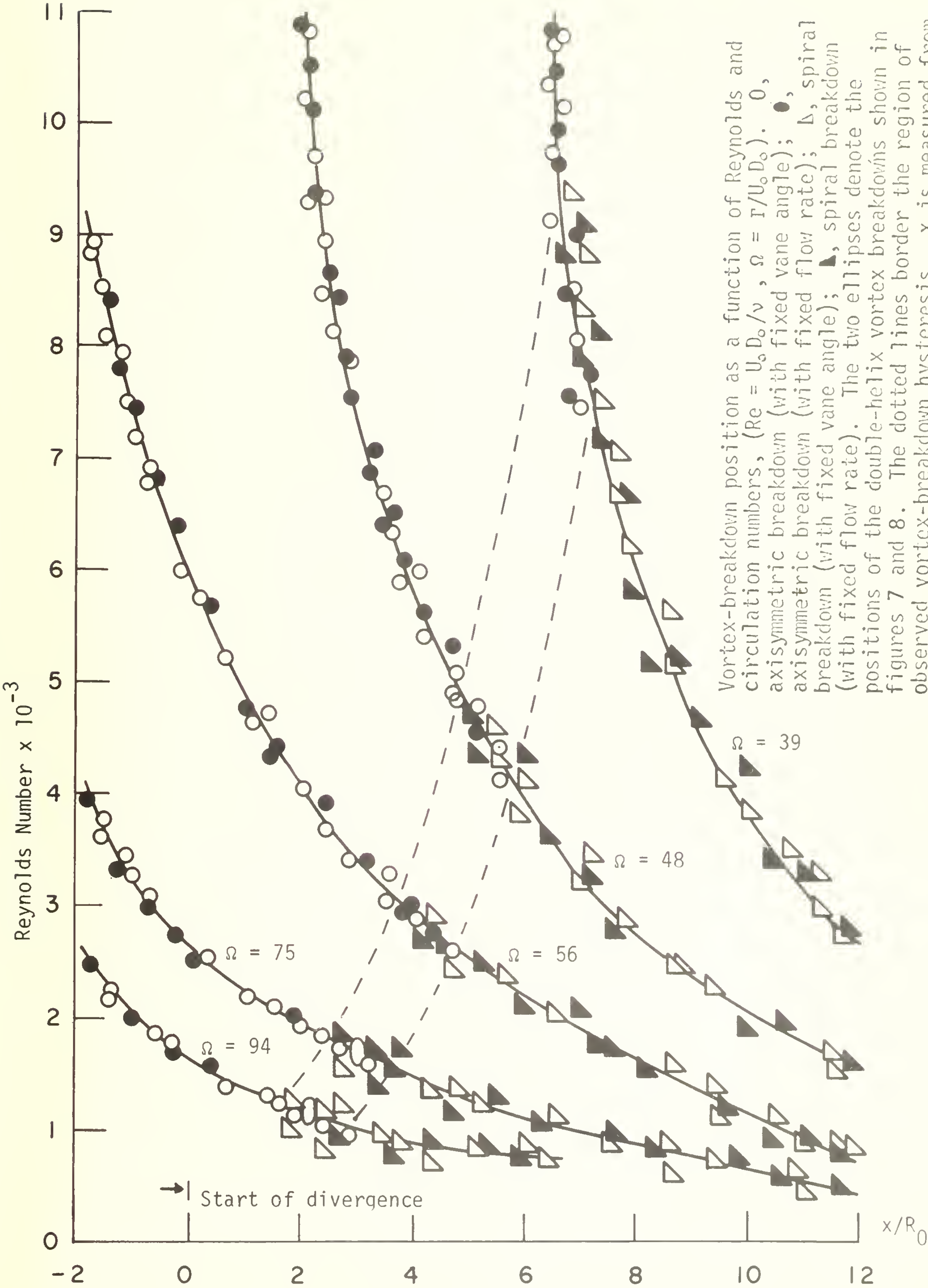


FIG. 21 This picture shows the swelling of the vortex-core filament, disappearance of the dye filament immediately downstream of the bubble, and the evolution of a gyrating tail. Frames follow from top to bottom starting at the upper left hand corner. The film speed is 16 frames/sec.




Vortex-breakdown position as a function of Reynolds and circulation numbers, ($Re = U_o D_o/\nu$, $\Omega = \Gamma/U_o D_o$). O, axisymmetric breakdown (with fixed vane angle); ●, axisymmetric breakdown (with fixed flow rate); ◺, spiral breakdown (with fixed vane angle); ◣, spiral breakdown (with fixed flow rate). The two ellipses denote the positions of the double-helix vortex breakdowns shown in figures 7 and 8. The dotted lines border the region of observed vortex-breakdown hysteresis. x is measured from the start of the diverging tube. The tip of the center body is at $x/R_o = -4.50$.

FIG. 22 (See insert for explanation)

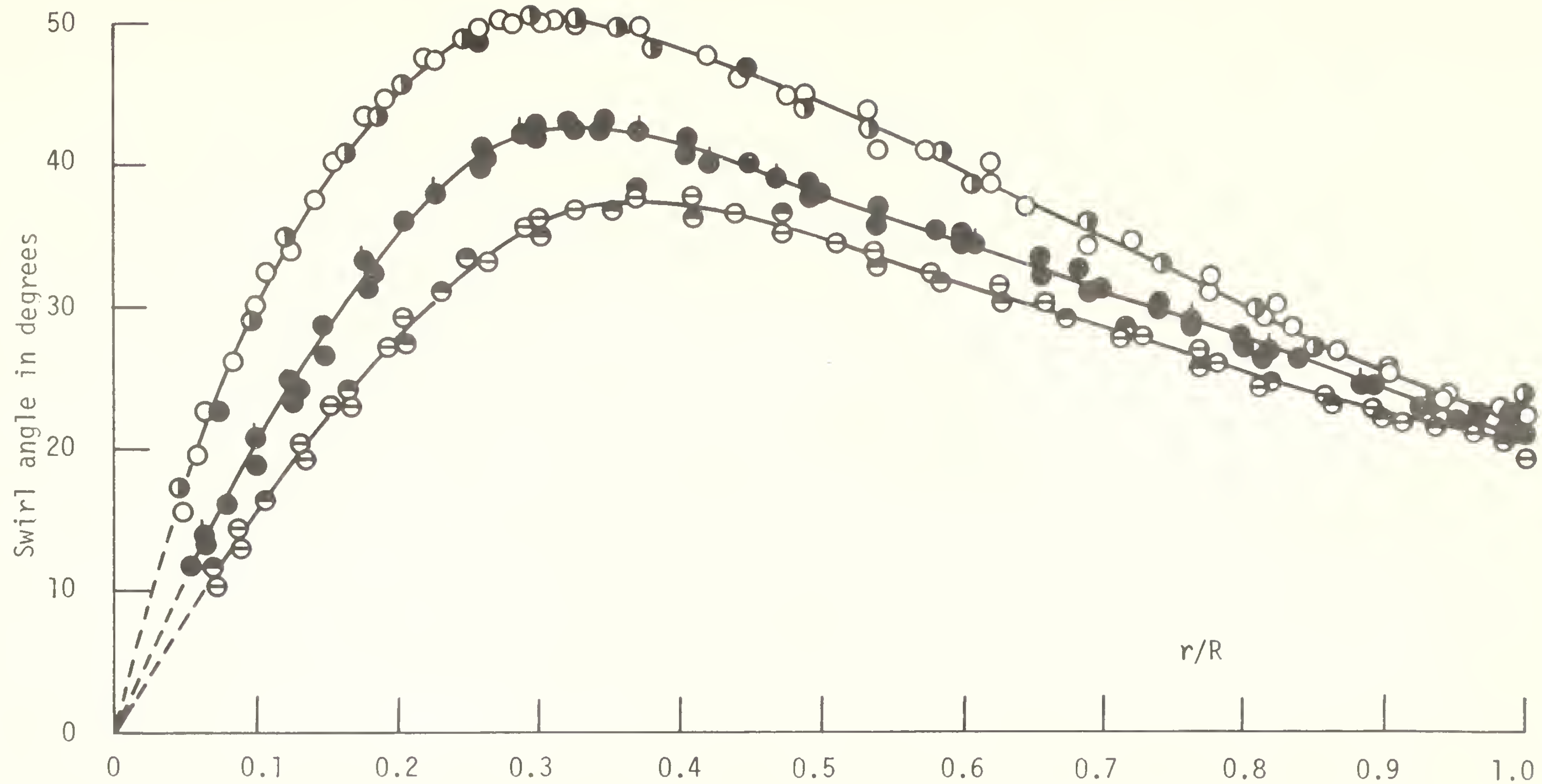



FIG. 23 Swirl angle distribution. R is the local radius of the tube where the swirl angle is measured. O, for Re = 4000 and Ω = 56; ◐, for Re = 7500 and Ω = 48; ●, for Re = 1500 and Ω = 56; ●, for Re = 4000 and Ω = 39; ●, for Re = 2200 and Ω = 56; and θ, for Re = 6000 and Ω = 39.

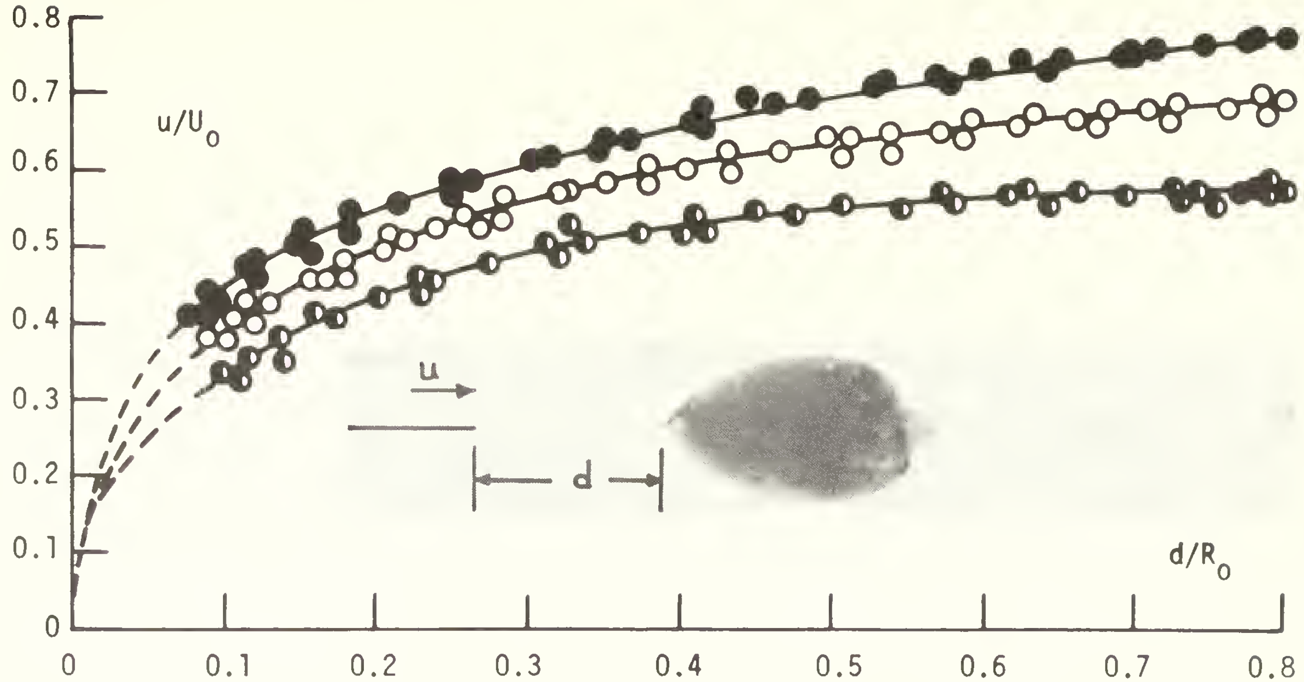



FIG. 24 The velocity of the vortex-core filament in terms of the relative distance from the bubble. ●, for Re = 4000 and Ω = 56; O, for Re = 7500 and Ω = 48; and ◐, for Re = 4000 and Ω = 39.

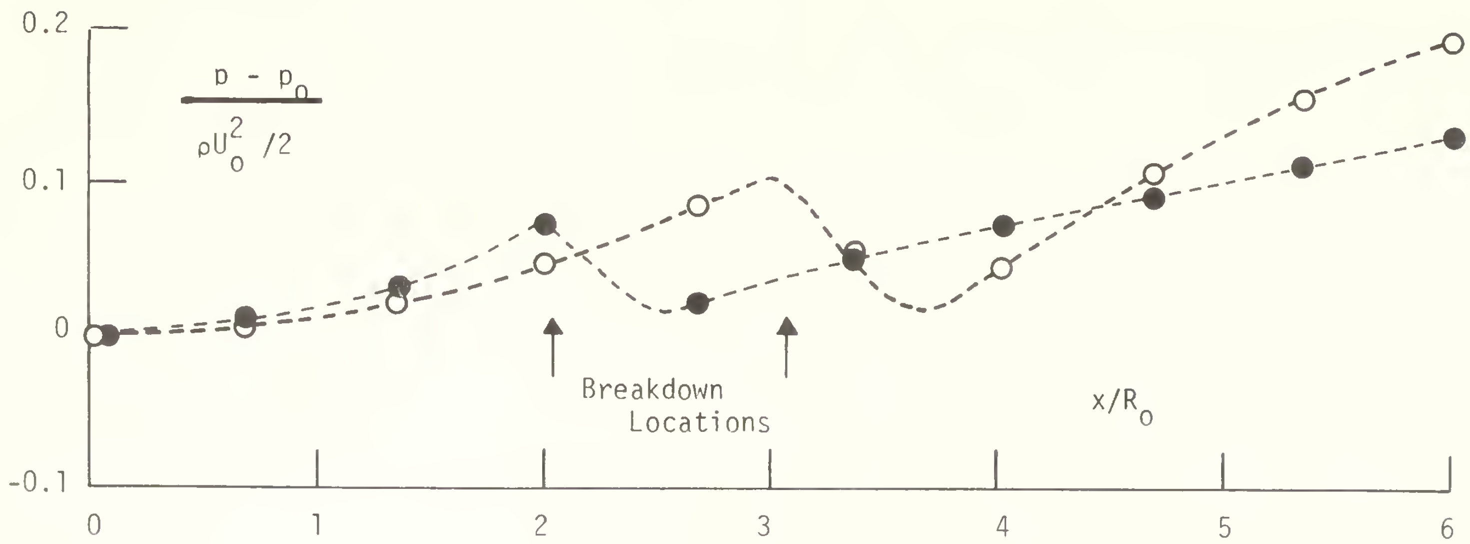



FIG. 25 Representative wall pressure distributions. $p_o$ denotes the pressure at the start of the diverging tube. O, for Re = 7500 and $\Omega$ = 48; and ●, for Re = 4000 and $\Omega$ = 56.

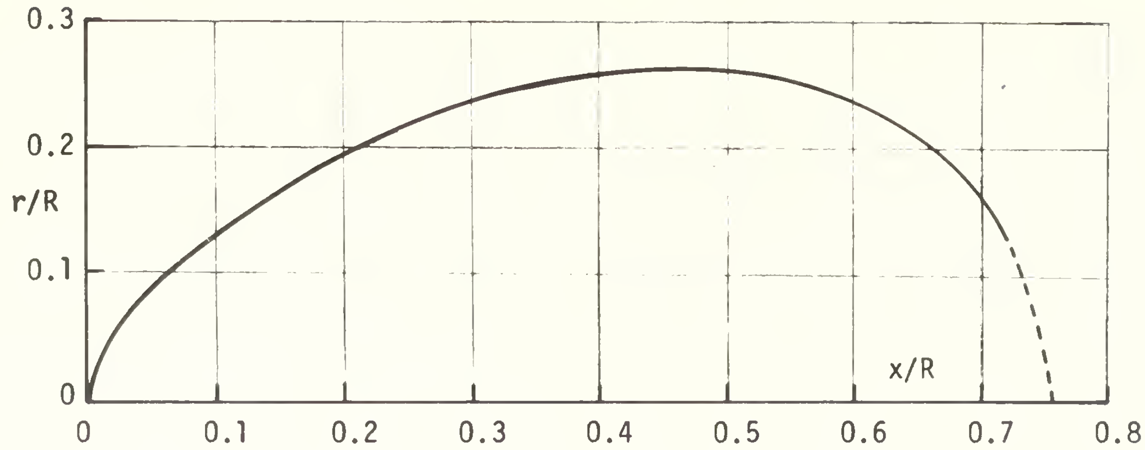



FIG. 26 THE CONTOUR OF A REPRESENTATIVE BREAKDOWN BUBBLE

(Bubble is assumed to be symmetric)

R = tube radius at the front stagnation point of the bubble.

# REFERENCES


1. HALL, M.G. The Structure of Concentrated Vortex Cores. Article in Progress in Aeronautical Sciences, 7, edited by Küchemann et al, Pergamon Press, 1966.

2. WERLÉ, H. Sur l'éclatemant des tourbillons d'apex d'une aile delta aux faibles vitesses. La Recherche Aeronautique, pp 23-30, No. 74, 1960.

3. ELLE, B.J. On the Breakdown at High Incidences of the Leading Edge Vortices on Delta Wings. Journal of the Royal Aeronautical Society, p 491, Vol. 64, 1960.

4. PECKHAM, D.H. Low Speed Wind Tunnel Tests on a Series of Uncambered Slender Pointed Wings with Sharp Edges. ARC RM 3186, 1961.

5. EARNSHAW, P.B. and LAWFORD, J.A. Low Speed Wind Tunnel Experiments on a Series of Sharp Edged Delta Wings. Part I. Forces, Moments, Normal Force Fluctuations and Positions of Vortex Breakdown. RAE TN Aero 2780, 1961.

6. ELLE, B.J. An Investigation at Low Speed of the Flow near the Apex of Thin Delta Wings with Sharp Leading Edges. ARC RM 3176, 1961.

7. LAMBOURNE, N.C. and BRYER, D.W. The Bursting of Leading Edge Vortices. Some Observations and Discussion of the Phenomenon. ARC RM 3282, 1962.

8. EARNSHAW, P.B. Measurements of Vortex Breakdown Position at Low Speed on a Series of Sharp-Edged Symmetrical Models. RAE Technical Report No. 6407, 1964.

9. LOWSON, M.V. Some Experiments with Vortex Breakdown. Journal of the Royal Aeronautical Society, pp 343-346, Vol. 68, 1964.

10. HUMMEL, D. Unterschuchungen über das Aufplatzen der Wirbel en schlanken Deltaflugeln. Zeitschr. Flugwiss., S 158-168, Vol. 13, 1965.

11. HUMMEL, D. and SRINIVASAN, P.S. Vortex Breakdown Effects on the Sow-speed Aerodynamic Characteristics of Slender Delta Wings in Symmetrical Flow. Journal of the Royal Aeronautical Society, pp 319-322, Vol. 71, 1967.

12. HARVEY, J.K. Some Observations of the Vortex Breakdown Phenomenon. Journal of Fluid Mechanics, 14, 585, 1962.

13. JONES, J.P. The Breakdown of Vortices in Separated Flow. University of Southampton U.S.A.A. Report No. 140, 1960.

14. LAMBOURNE, N.C. The Breakdown of Certain Types of Vortex. N.P.L. Aero Report 1166, 1965.

15. LUDWIEG, H. Zur Erklärung der Instabilität der über angestellten Deltaflügeln auftreten freien Wirkbelkerne. Zeitschr. Flugwiss., 10, 242, 1962.

16. LUDWIEG, H. Explanation of Vortex Breakdown by the Stability Theory for Spiralling Flows. Paper presented at IUTAM Symposium on Vortex Motions, Ann Arbor. Available as AVA-Bericht 64 A 14, 1964.

17. JONES, J.P. On the Explanation of Vortex Breakdown. Paper presented at IUTAM Symposium on Vortex Motions, Ann Arbor, 1964.

18. BENJAMIN, T.B. Theory of the Vortex Breakdown Phenomenon. Journal of Fluid Mechanics, 14, 593, 1962.

19. BENJAMIN, T.B. Significance of the Vortex Breakdown Phenomenon. Trans. Am. Soc. Mech. Engrs., Journal of Basic Engineering, 87, 518 and 87, 1091, 1965.

20. BENJAMIN, T.B. Some Developments in the Theory of Vortex Breakdown. Journal of Fluid Mechanics, 28, 65, 1967.

21. FRAENKEL, L.E. On Benjamin's Theory of Conjugate Vortex Flows. Journal of Fluid Mechanics, 28, 85, 1966.

22. SHEER, A.F. On the Nature of Conjugate Vortex Flows. Journal of Fluid Mechanics, 33, 625, 1968.

23. JONES, J.P. An Examination of the Hydraulic Jump Theory of Vortex Breakdown. University of Southampton U.S.A.A. Report No. 265, 1966.

24. GRANGER, R.A. Speed of a Surge in a Bathtub Vortex. Journal of Fluid Mechanics, 34, 651, 1968.

25. PRITCHARD, W.G. Solitary Waves in Rotating Fluids. Journal of Fluid Mechanics, pp 61-83, Vol. 42, part 1, 1970.

26. HALL, M.G. On the Occurrence and Identification of Vortex Breakdown. R.A.E. Technical Report No. 66283, 1966.

27. GARTSHORE, I.S. Some Numerical Solutions for the Viscous Core of an Irrotational Vortex. N.R.C. (Canada) Aero. Report LR-378, 1963.

28. GORE, R.W. and RANZ, W.E. Backflows in Rotating Fluids Moving Axially through Expanding Cross Sections. American Institute of Chemical Engineers Journal, 10, 83, 1964.

29. BOSSEL, H.H. Vortex Breakdown Flowfield. The Physics of Fluids, pp 498-508, Vol. 12, No. 3, 1969.

30. LEIBOVICH, S. Private communication. The paper titled "Weakly Non-Linear Waves in Rotating Fluids" by Leibovich will appear in the Journal of Fluid Mechanics.

31. KIRKPATRICK, D.L.I. Experimental investigation of the breakdown of a vortex in a tube. R.A.E. Tech. Note No. Aero 2963, 1964.

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13. ABSTRACT

The results of an experimental investigation of the characteristics of stationary and travelling vortex breakdowns in swirling flow in a diverging cylindrical tube are presented and discussed. Basically, three types of vortex breakdown were observed, viz., double helix, spiral, and axisymmetric breakdown. The type and location of the stationary breakdowns were found to be dependent upon the Reynolds and circulation numbers of the flow. The breakdown bubble responded to gradual and abrupt changes in the upstream and downstream flow conditions in a manner analogous to the hydraulic jump in open-channel flow. The observations reported and the evidence presented herein revealed unmistakably that the vortex breakdown is a finite transition from a uniform state of swirling flow (supercritical) to one (subcritical) featuring a large standing wave, followed by standing wavelets, of finite amplitude.

| 14 KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Vortex Breakdown | | | | | | |
| Waves in Swirling Flows | | | | | | |